

# COMPARISON OF HOST RADAR POSITIONS TO GLOBAL POSITIONING SATELLITE POSITIONS

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## Abstract

The Federal Aviation Administration (FAA) air traffic control system relies directly on aircraft locations provided by the long range en route surveillance radars. The accuracy of the radars is an important factor in determining the overall performance of the system. To support the planned modernization of the air traffic control system a study was conducted to measure the accuracy of the radar tracking function of the current system. The aircraft radar tracks were compared to the positions produced by the Global Positioning Satellite System (GPS), which was considered the true aircraft position. The GPS data was available from the FAA's Reduced Vertical Separation Minimum Certification Program. Utilizing the Host Air Traffic Management Data Distribution System at each Air Route Traffic Control Center that captures the radar tracking data, 265 flight's of radar tracking data were compared to their GPS positions. Three distance metrics were used. The time coincident straight line distance, referred to as the horizontal track error, and its two orthogonal components: cross track error (side to side error) and along track error (longitudinal error) were calculated. A total of 54,170 measurements were taken. This resulted in an average horizontal error of 0.69 nautical miles, an average (unsigned) cross track error of 0.12 nautical miles, and an average (unsigned) along track error of 0.67 nautical miles.

## Introduction

The Federal Aviation Administration (FAA) is upgrading its Air Traffic Control (ATC) system and plans to replace the existing Host system. The Host Computer System (HCS) is the main frame computer operating in all twenty en route ATC Centers in the continental United States. This paper describes how the Host's tracking of radar surveillance data was compared to time coincident Global Positioning Satellite System (GPS) aircraft positions. The results establish a baseline accuracy

of the Host's radar tracking function and in turn provide a performance standard for the FAA's modernization efforts.

## Previous Studies

Previous studies have used simulation methods to provide metrics on Host radar tracking accuracy. Most notably, a study was completed by Trios Corporation in November 2003 [1]. Their study developed a wide array of metrics related to radar tracking defined as quantifiable measurements of performance (MOPs). The most relevant MOPs to this study directly evaluated the Host radar tracker's positional accuracy using a series of simulation runs using the FAA's Interfacility and Radar System simulation tool. The study examined two target motion states: steady state and maneuver state. Steady state referred to level and straight flight and maneuver state referred to time periods when the target underwent heading or speed changes, or time periods in which the tracker's statistical behavior was not in steady state.

This Trios study found an rms<sup>1</sup> error of 0.2 to 0.5 nm at a speed of 600 knots on a straight track and an error of 1.6 to 1.7 nm rms during turns. These Trios simulation results will later be compared to the results found in this study based on operational data.

## Scope

A large sample of aircraft flights from all of the 20 Air Route Traffic Control Centers (ARTCCs or Centers) were selected for the tracking comparison. The differential GPS data for these flights was available from the Reduced Vertical Separation Minimum (RVSM) Certification Group

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<sup>1</sup> The root-mean-square (rms) is the square root of the sample mean of squared errors. It is proportional to the sample mean of the unsigned metrics but tends to more heavily weight the upper and lower tails of the distribution.

at the FAA's William J. Hughes Technical Center (WJHTC) [2]. The recorded radar track data for these flights was obtained from an FAA server that maintains recordings of the radar tracks for all of the Centers for the last several months. The comparison was done in the horizontal plane only; the differences in reported altitudes were not addressed in this study. For this study, the GPS data is considered to be the true position of an aircraft and the difference between the GPS data and the radar data is considered to be the Host's radar tracking error.

This paper describes the data collection, reduction, and analysis processes that took place. The data collection process assembled the input Host tracks and GPS position reports from external sources. The data reduction process matched and re-formatted the data for application in legacy software tools. The data analysis applied statistical methods and examined individual sample flights to draw conclusions on the Host tracker's accuracy.

## Data Collection

The overall process applied in this study is illustrated in Figure 1. The radar track data from each of the Host Computer Systems was recorded by the Host Air Traffic Management (ATM) Data Distribution System (HADDs) and archived in a network server at the WJHTC. This data was made accessible via a secure link to the authors of this paper by the En Route Peripheral Systems Branch (AOS-330) who maintains the system. Utilizing the search capabilities of the HADDs Server, the Host's radar tracks for specific flights were acquired, which were identified from the GPS data set. In summary, as illustrated in Figure 1, the process included: (1) selection of the specific flights to request, (2) acquisition of the data by utilizing the HADDs Server and querying for the identified flights, and finally (3) processing the flight data into the form required by legacy data analysis tools.

To date, the RVSM Certification Group at the WJHTC has certified approximately 10,000 aircraft to fly in RVSM airspace. The certification process entails recording and processing the GPS position of the aircraft for about 40 minutes while it is in straight and level cruise. For this study, the RVSM Certification Group provided approximately 400 flights from January 3<sup>rd</sup> through February 25<sup>th</sup> 2005. Relatively recent flights were chosen to ensure that their Host tracking data would be available. The GPS data for each flight after processing by the RVSM Certification Group were recorded in an ASCII data file. Each flight was identified by a sequence number and start/end times determined. Some of the flights were made specifically for RVSM certification and others during regular operations, so some vertical transitions were present as well.

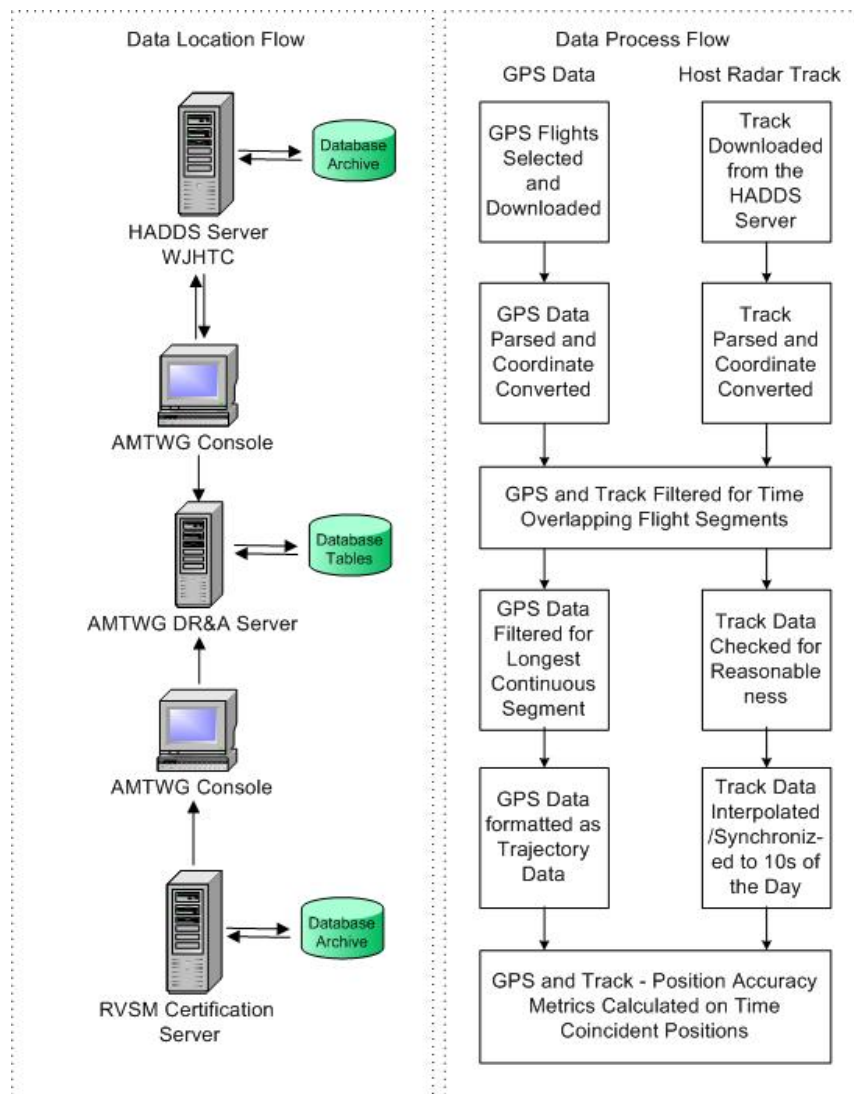
## Data Acquisition

The Host's radar track data is recorded by the HADDs as a sequence of messages using the format of the Common Message Set (CMS) [3]. As illustrated in Figure 1, the radar track data was queried for the selected aircraft and date and downloaded manually, one day at a time. Thus, all of the CMS messages for the selected flights in all of the Centers on a specific day were downloaded into a single file. A given flight might fly through, several Centers, while the GPS recorded portion of the flight may go through only a subset of these Centers. Since the legacy tools required processing on individual Centers, flight segments were grouped into their respective Centers from all the specific dates and flights downloaded.

The process also discarded flight segments<sup>2</sup> that did not have matching GPS data. For the example, only the flight segments in the Centers common to both GPS and Host would be retained for further analysis.

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<sup>2</sup> For this study there is a distinction between a flight and flight segments. A flight may travel through many Centers, but a flight segment is just the portion of the flight within a Center.



**Figure 1. Data Process Flow**

## Data Reduction

A number of computer processing steps were necessary to prepare the data for comparison. Most of the software used in this study was adapted from tools developed for previous studies to examine the trajectory accuracy of decision support tools [4]. Since the legacy tools were designed to process only one Center's flight segments at a time by comparing radar track and trajectory predictions, it was necessary to alter the format of the GPS data to match the legacy trajectory formats. Before the comparison of the radar track and GPS was performed, several preprocessing steps were executed. They included: (1) filtering the radar track data to match the available duration of GPS

data, (2) segregating the data by Center, and (3) converting the positional data from longitude and latitude coordinates to positions in the Center specific stereographic coordinate system. The subsequent subsections will describe the details of these processing steps.

### *Conversion of GPS to Legacy Formats*

The FAA's legacy analysis tools originally compared radar track data to trajectories (predicted flight paths). They were modified for this study to compare the radar data to the GPS data. This required the GPS data to be converted to the same format as trajectory data. As with the radar data, an important part of the processing was the conversion

of the latitude and longitude aircraft positions into stereographic XY positions. Each Center has its own unique stereographic coordinate system and therefore it was essential to know the Center identification for every GPS position report. Therefore, the processing used time to match Host radar track data that was already segregated by Center to the GPS position reports and in turn determine the Center to use for the coordinate conversion.

The GPS data was nominally sampled at a one-second sampling rate. However, many flights contained time gaps of much larger durations. For each GPS flight, the longest contiguous segment of position reports were identified and saved; the rest of the data was discarded. A contiguous segment was defined to be one in which there were no gaps longer than ten seconds. The longest segment of position reports for each GPS flight was written to a relational database table along with its identifying information. Approximately 15% of the data was discarded during this process to obtain contiguous GPS data.

Once all of the GPS data for all the selected flights was stored to the database, another software program extracted the data to 10-second intervals and stored the data in flat files, one for each Center, consistent in format with legacy software tools. Now segregated by Center, each of these GPS data files provided the input for the comparison with the radar track data.

### ***Processing of Radar Track Data***

As illustrated in Figure 1, in the data process flow stream of the Host radar track, the data is first extracted and downloaded from the HADDS Server, then parsed and converted to the XY coordinate frame. Since the flights are extracted for all Centers they fly through, the flights are segregated by Center into flight segments. Next, these flight segments of track are compared to the GPS data and filtered for time overlap accordingly. This step may eliminate flight segments in which GPS was not available. Unlike the GPS data, which is fairly smooth and clean, Host track data may contain gross errors due to lags in the recording process or other anomalous reasons. Thus, the track data is run through a post-processing tool that checks for reasonableness. This is documented in

detail in Reference [5]. Finally, the track reports are interpolated to 10-second intervals and synchronized to the hour of the day. This step is in preparation for later comparison to its companion GPS data.

### **Comparison Processing**

After the collection and preprocessing of the radar and GPS data, the two input sources for each Center was ready for processing by the FAA's legacy software tools that calculate the error metrics. The radar track data, which was now coordinate-converted, checked for reasonableness, interpolated, and time synchronized to 10-second intervals, resided in a set of relational database tables. The GPS positions were now parsed, coordinate-converted, sampled at 10-second intervals, and formatted into trajectory files.

### ***Application of Interpolation for Time Coincidence***

To calculate the time coincident spatial metrics (which will be defined in the next section) both the radar track data and GPS positions not only had to be in the same coordinate frame, but also synchronized to the same time positions. The radar track data was already time synchronized to 10-second intervals on the hour. However, the GPS trajectory positions were sampled at 10-second intervals but not synchronized to the hour. The software tool responsible for the comparison processing first linearly interpolated the GPS positions to synchronize them to same 10-second intervals as the radar. Next, each aircraft's particular radar flight segment within the Center were matched by time to the GPS positions and forwarded to the next process that calculates the spatial metrics.

Even though the GPS positions were originally supplied at 1-second time intervals and would not require any interpolation, due to compatibility issues with legacy software tools, it was necessary to sample the GPS data at 10-second intervals and then later use interpolation to time synchronize to the track data. It was determined that the impact of these two steps on the study results to be negligible.

## ***Spatial Metrics***

Matched and synchronized in the previous step, each radar track position of an aircraft was compared to the time coincident GPS position of the aircraft. Three metrics were calculated for each pair of reports: (1) horizontal error, (2) along track or longitudinal error, and (3) cross track or lateral error. The details of the computation have been given in References [6] and [7]. In summary, horizontal error is the unsigned straight line distance between the time coincident radar track and GPS position. Along and cross track errors are the signed orthogonal components of the horizontal error. Along track is the longitudinal component of the horizontal error. A positive value indicates the track is ahead of the GPS position and negative that it is behind the time coincident GPS report. The cross track error is the lateral or side to side error component of the horizontal error. A positive cross track error indicates the track is to the right of the GPS position and negative is to the left.

A data processing run was made for each of the 20 Centers. Each run populated a relational database table with the position errors for all of the matched radar reports for all of the flights in that Center. A GPS flight which flew through more than one Center's airspace has part of its error data assigned to each of the airspaces that it traverses. For analysis purposes, the 20 metric tables were combined into a single database table. The next section summarizes the analysis of this table.

## **Data Analysis**

The data analysis included three methods to evaluate the spatial metrics discussed above. Descriptive statistics were applied to specify the sample population of these measurements, defining the Host tracker's accuracy. Inferential statistical methods were applied to evaluate if other factors had an impact on the Host tracker's accuracy. Finally, two individual flight samples were examined in detail to complement the statistical analyses and illustrate the errors for the reader.

The original 400 flights resulted in 54,170 pairs of measurements from 265 flights. Partitioning the flights by Center into flight segments produced a total of 391 flight segments.

A small number of outliers were excluded from this data. The outliers did not represent the basic accuracy of the Host radar tracking capabilities and represented artifacts produced from the data collection process. For example, in some of these cases mismatches of the flight identification caused the incorrect matching of GPS to radar tracking data. To remove these errors, flight segments that had a maximum horizontal error of greater than 2.0 nm were categorized as outliers. Twenty three of the 414 flight segments were excluded in this way (414-23=391), representing 5.8 % of the measurements.

## ***Descriptive Statistics***

The descriptive statistics summarize and quantify the accuracy data collected for the horizontal and along and cross track error metrics. The statistics used in this study include average, rms, standard deviation, and quantiles taken from the sample of flight segments. The accuracy data are also illustrated by histograms in Figure 2-4. These statistics have been calculated for all flight segments and later applied to individual samples.

### **Overall Error Rates**

The overall error rates for all flight segments and all measurements are listed in Table 1. The signed error values tend to cancel out in some statistics (for example, the sample mean). Therefore, Table 1 provides both the signed and unsigned values for cross and along track statistics. The average signed cross track error is practically zero (very small at about 100 feet) while the average unsigned (magnitude) cross track error is significantly larger (700 feet). However, the signed and unsigned averages for the along track error are similar in magnitude, since along track errors are consistently negative. It is believed that in this data an along track error represents a time error. This data therefore indicates that the HCS track report's time stamping has an uncompensated error. At a speed of 420 knots, an error distance of 0.67 nm corresponds to time error of about 6 seconds.

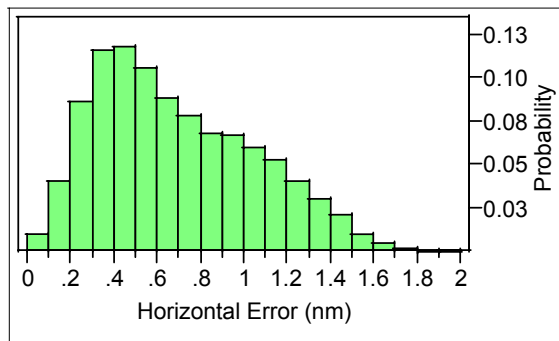
In Table 1, the rms for horizontal error was about 0.1 nm higher than the sample mean. The differences are similar for the other metrics.

**Table 1. Sample Mean and RMS Statistics for All Flight Segments**

		Horizontal Error (nm)		Cross Track Error (nm)		Along Track Error (nm)	
Type	Sample Size	Mean	RMS	Mean	RMS	Mean	RMS
Signed	54170	0.69	0.78	0.00	0.16	-0.67	0.77
Unsigned				0.12		0.67	

### Overall Horizontal Error

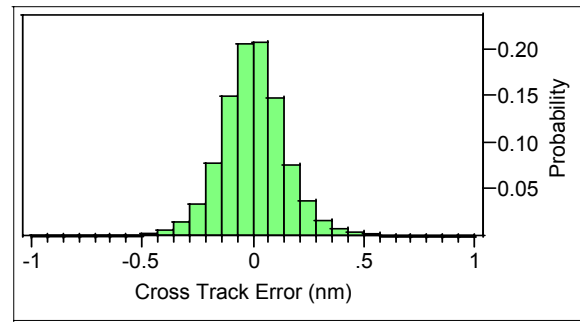
The horizontal error distribution in Figure 2 is skewed with a peak around 0.4 nm, sample mean 0.69 nm, and median 0.63 nm. Horizontal error is an unsigned metric by definition, so the skew is a result of the combination of its two orthogonal components; the along and cross track errors. The standard deviation of the horizontal error is 0.36 nm. The 75<sup>th</sup> and 25<sup>th</sup> quantiles are 0.95 nm and 0.40 nm, respectively.



**Figure 2. Histogram of Horizontal Error**

### Overall Cross Track Error

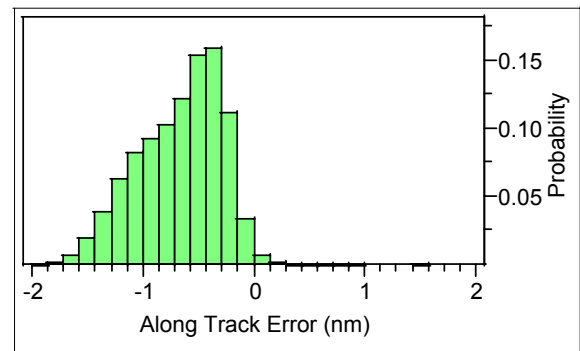
As shown in Figure 3, the cross track error is a signed metric that is symmetric around a population mean close to zero. The sample mean is for all practical purposes zero and sample standard deviation of 0.16 nm. The sample median is very close to zero as well and the 75<sup>th</sup> and 25<sup>th</sup> quantiles are 0.09 nm and -0.09 nm, respectively. All indicate a very symmetric Gaussian type distribution around zero.



**Figure 3. Histogram of Cross Track Error**

### Overall Along Track Error

As shown in Figure 4, the along track error is another signed metric like the previous cross track error, but unlike the very symmetric cross track error the along track distribution is significantly negatively skewed. It has a sample mean -0.67 nm and median of -0.61 nm. The standard deviation is 0.38 nm and the 75<sup>th</sup> and 25<sup>th</sup> quantiles are -0.37 nm and -0.94 nm, respectively. Thus, the along track error not only provides the magnitude of the error but illustrates the inherent lag in the Host tracker's smoothing of the aircraft positions.



**Figure 4. Histogram of Along Track Error**

## Inferential Statistics

Inferential statistics are methods that go beyond summarizing the sample like the previous section but have an objective to draw conclusions about the population based on the sample information [8]. They are used to test for a specific question or series of questions by determining if a given predictor variable influences the response variable [9].

In this study, the response variables include the horizontal, cross track, or along track errors and the predictor variables include the Center, turn status (i.e. the track is within a turn or not), vertical transition status (i.e. track is climbing, descending or level), or altitude interval. Therefore, the inferential analysis provides statistical evidence whether a variable influences the HCS tracker's performance.

An example of one of these analyses is the influence of Center on the error metrics. In Table 2, the average and standard deviation of horizontal

track error and signed cross and along track errors were listed for each Center. The listing illustrates the modest variation of the magnitude of the tracker errors across all 20 Centers. A statistical test compared the 190 paired combinations of the sample means between all 20 Centers and did show that some were statistically different. However, the magnitude of the difference ranging from close to zero to about 0.2 nautical miles (approximately 1200 feet) did not provide sufficient evidence to conclude that tracker accuracy was impacted by the Center the aircraft operated in.

**Table 2. Track Error Statistics by Center**

		Horizontal Error		Cross Track Error		Along Track Error	
Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Albuquerque	1840	0.83	0.36	0.02	0.13	-0.82	0.37
Chicago	1791	0.69	0.43	0.04	0.17	-0.66	0.45
Boston	1946	0.71	0.36	-0.01	0.13	-0.70	0.36
Washington	3106	0.78	0.39	0.08	0.24	-0.73	0.40
Denver	3411	0.68	0.31	-0.01	0.19	-0.65	0.32
Fort Worth	2227	0.81	0.40	0.01	0.13	-0.79	0.40
Houston	4567	0.63	0.35	-0.02	0.15	-0.61	0.36
Indianapolis	4351	0.68	0.36	0.01	0.16	-0.66	0.37
Jacksonville	1879	0.66	0.36	-0.02	0.13	-0.63	0.39
Kansas City	10721	0.62	0.35	0.00	0.13	-0.60	0.36
Los Angeles	2784	0.74	0.35	-0.01	0.12	-0.73	0.35
Salt Lake City	1101	0.67	0.32	0.01	0.18	-0.64	0.33
Miami	3057	0.72	0.32	-0.04	0.14	-0.70	0.33
Memphis	1253	0.60	0.40	0.01	0.17	-0.56	0.43
Minneapolis	2859	0.69	0.37	0.02	0.14	-0.66	0.40
New York	593	0.62	0.33	-0.03	0.19	-0.56	0.36
Oakland	1276	0.73	0.38	-0.03	0.16	-0.70	0.39
Cleveland	1651	0.72	0.33	-0.01	0.14	-0.69	0.35
Seattle	172	0.66	0.30	0.02	0.13	-0.65	0.31
Atlanta	3585	0.73	0.38	0.00	0.15	-0.71	0.39

## Illustrative Flights

To complement the statistical analyses performed on all flights; this section presents a detailed overview of two flights within the study. The first flight has a substantial quantity of calculated metrics with errors representative of a typical flight. It has a long flight segment flying through Kansas City Center (ZKC) with overlapping GPS data. The second flight sample has less calculated metrics but relatively large cross track errors.

### *Sample Flight Number One*

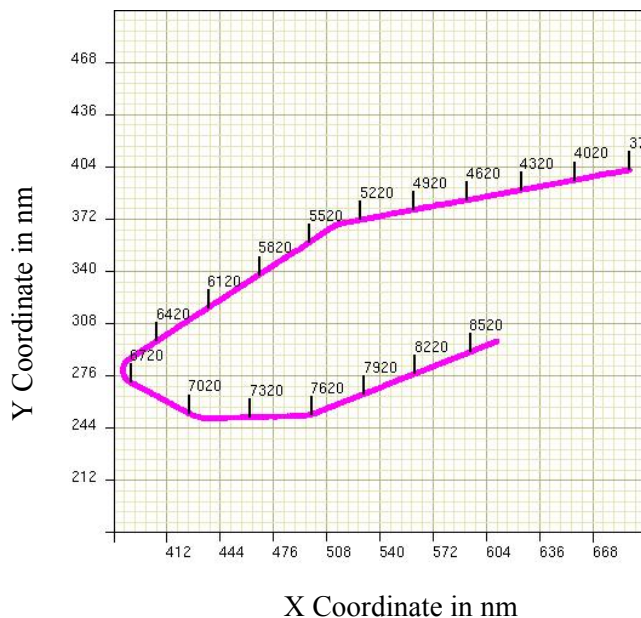
For the first sample, a flight segment having average horizontal error was selected to illustrate

the comparison of the radar track to the GPS track. The aircraft was a business jet, a Falcon Mystere 900. The flight was flown from Springfield Illinois to Kansas City Missouri, to Wichita Kansas, to a Fayetteville Arkansas radial, and back to St. Louis Missouri. The segment analyzed is in ZKC. In fact, the entire flight captured in the recorded data is in ZKC.

### **Radar Data**

The HADDs radar track is shown in Figure 5. The X and Y coordinates are the stereographic coordinates of the local Center, ZKC in this case.





**Figure 5. Radar Horizontal Flight Path - #1**

The numbered vertical lines along the plot are time stamps in seconds of Coordinated Universal Time (UTC), separated at 10-second intervals. The flight duration is 01:22:20 (4940 seconds). The aircraft climbs to a cruising altitude of Flight Level (FL) 350 and later on climbs to and cruises at FL 370.

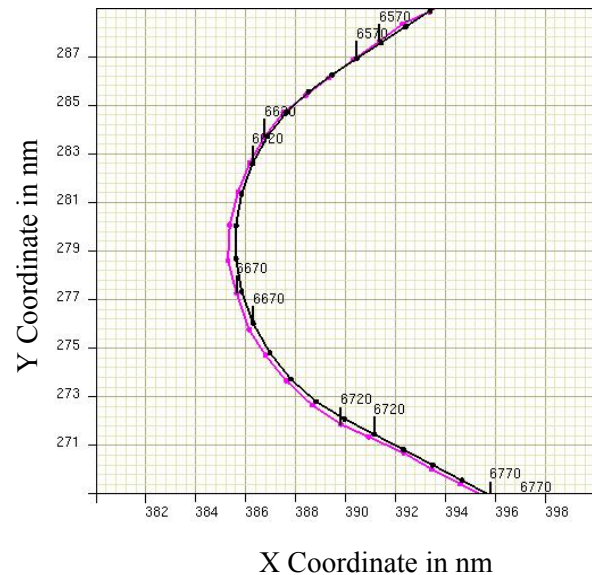
#### GPS Data

The GPS part of the flight is in level cruise, first at FL 350 and then at FL 370. The GPS flight segment starts at 00:58:26 (3506 seconds) UTC and ends at 02:24:25 (8665 seconds) UTC, a duration of 01:25:59 (5159 seconds). The longest contiguous segment after re-sampling starts at 01:22:00 (4920 seconds) and ends at 02:23:20 (8600 seconds), a duration of 01:01:20 (3680 seconds). The first part of the GPS track has been discarded because of gaps in the data.

#### Data Analysis

The three metrics were calculated for every radar position report for which there was a time matched GPS position report. For this sample flight there are 374 horizontal position error measurements. At the resolution in Figure 5 the two sets of position data lie on top of each other. An expanded plot is shown in Figure 6 for the turn at the western end of the track. At this expanded scale the differences between the position reports can be seen. The radar track lags the GPS track in the turn by about ten seconds. In the turn the horizontal

error is about 1.4 nm. The radar track swings wide in the turn and is off laterally by about 0.33 nm. Later in the flight the aircraft is flying straight and level, but the radar track still wanders from side to side. On this straight part of the flight, the lag as shown by the time tags is very small. This behavior is illustrated in Figure 7. The radar track wanders up to 0.18 nm away from the GPS track.

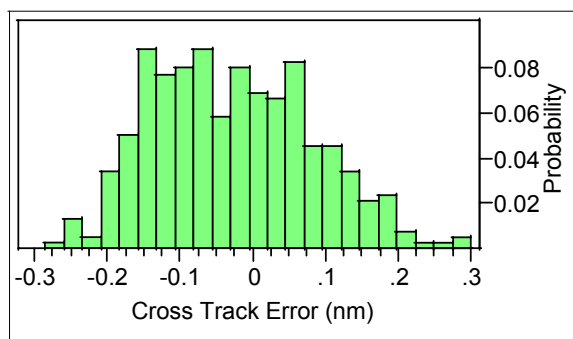




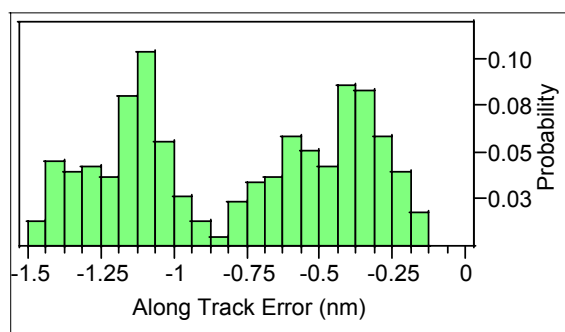
The descriptive statistics for Sample Flight #1 are presented in Table 3. The average cross track error is very close to zero and rms is 0.12 nm, which are both very close to the overall error statistics for all flights listed in Table 1. The distribution of the cross track errors for this flight segment is presented in Figure 8. The cross track errors are consistent with the overall cross track errors from Figure 3. They form a symmetric distribution with a mean close to zero nautical miles. The distribution of the along track errors for this flight segment is presented in Figure 9.

**Table 3. Sample Flight #1 Radar Track Errors**

		Horizontal Error (nm)		Cross Track Error (nm)		Along Track Error (nm)	
Type	Sample Size	Mean	RMS	Mean	RMS	Mean	RMS
Signed	374	0.80	0.89	-0.04	0.12	-0.79	0.88
Unsigned				0.10		0.79	



**Figure 8. Flight #1 - Cross Track Error**



**Figure 9. Flight #1 - Along Track Error**

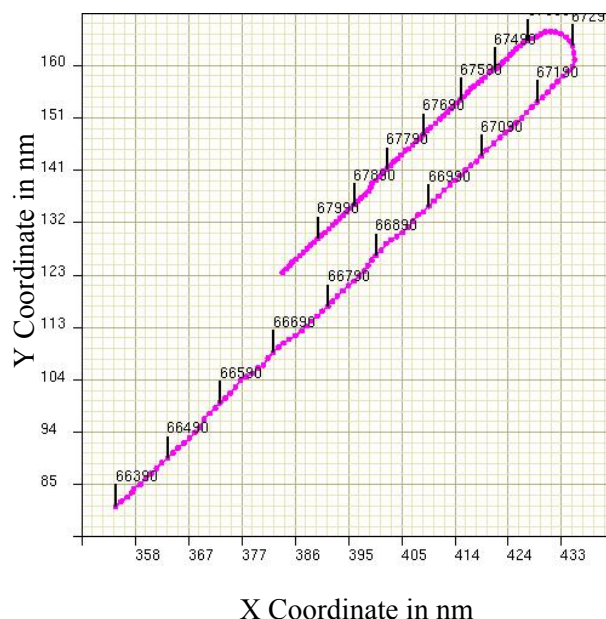
### Sample Flight Number Two

A second flight sample having a large lateral error has been selected to further illustrate the

comparison of radar track to GPS position reports. The aircraft is a business jet, a Falcon Mystere 10. The flight was flown from Knoxville Tennessee to Beckley West Virginia and back to Knoxville. The flight segment presented is in Indianapolis Center (ZID). It was a RVSM certification flight with a 180 degree turn.

### Radar Data

The Host radar track is shown in Figure 10. As discussed before, the X and Y coordinates are the stereographic coordinates of the local Center, ZID in this case. The time tags in the plot give the UTC seconds at the nodes which are spaced at 10 second intervals. The flight duration is 00:28:20 (1700 seconds). The aircraft initially is at FL 290 and later climbs to FL 310.



**Figure 10. Flight #2 - Horizontal Track Path**

### GPS Data

The GPS track data starts at 18:23:08 (66188 seconds) UTC and ends at 18:55:02 (68102 seconds) UTC. After selecting the longest contiguous segment and re-sampling, the data starts at 18:26:30 (66390 seconds) UTC and ends at 18:51:53 (67913 seconds) UTC, a duration of 00:25:23 (1523 seconds). Therefore, most of the data is contained in the longest contiguous segment.

### Data Analysis

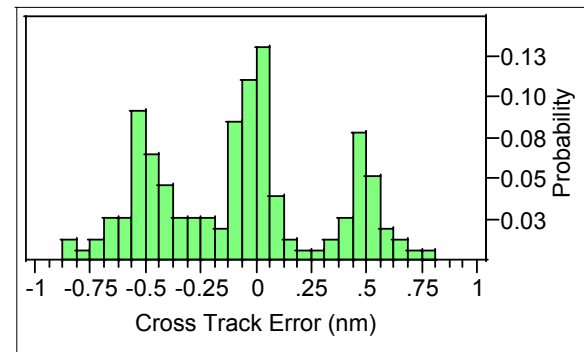
The radar track has noticeable cross track error. A portion of the flight is plotted in Figure 11

Figure 1 is a graph showing the Y Coordinate in nm versus the X Coordinate in nm. The X-axis ranges from 411 to 435 nm, and the Y-axis ranges from 141 to 165 nm. The graph displays two distinct paths, one solid black and one dashed pink, both showing a similar trajectory with a sharp turn. The paths are labeled with their respective coordinates at various points.

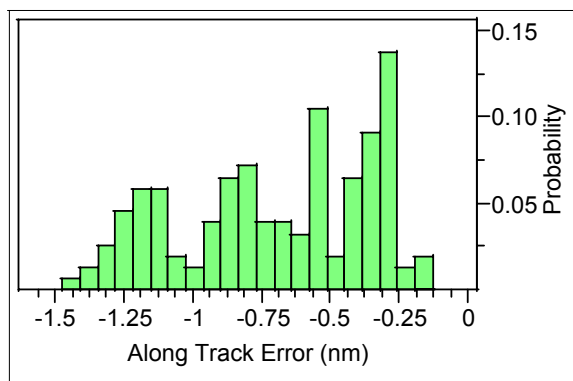
Path	X Coordinate (nm)	Y Coordinate (nm)
Black	411.5	148.5
Black	412.5	149.5
Black	414.5	153.5
Black	416.5	155.5
Black	418.5	157.5
Black	420.5	159.5
Black	422.5	161.5
Black	424.5	163.5
Black	426.5	164.5
Black	428.5	165.5
Black	430.5	165.5
Black	432.5	164.5
Black	434.5	161.5
Black	435.5	159.5
Pink	411.5	148.5
Pink	412.5	149.5
Pink	414.5	153.5
Pink	416.5	155.5
Pink	418.5	157.5
Pink	420.5	159.5
Pink	422.5	161.5
Pink	424.5	163.5
Pink	426.5	164.5
Pink	428.5	165.5
Pink	430.5	165.5
Pink	432.5	164.5
Pink	434.5	161.5
Pink	435.5	159.5

There were 153 error measurements taken for Flight #2. The descriptive statistics for this flight segment are listed in Table 4. As discussed above and listed in Table 4, the average unsigned cross track error and rms are significantly larger than the overall cross track error for all flights. This is further illustrated in Figure 13, which presents the distribution of cross track errors. From this figure, the cross track error is centered close to zero but with much larger variability than illustrated in Figure 3 for all flights.

		Horizontal Error (nm)		Cross Track Error (nm)		Along Track Error (nm)	
Type	Sample Size	Mean	RMS	Mean	RMS	Mean	RMS
Signed	153	0.82	0.88	-0.08	0.41	-0.70	0.79
Unsigned				0.32		0.70	



The along track errors are practically the same as the overall along track error for all flights. The overall along track rms error, as previously presented in Table 1, is 0.77 nm. For Flight #2, the along track rms is 0.79 nm. The along track error distribution for Sample Flight #2 is illustrated in Figure 14. Like the overall error, it is negatively skewed, representing a consistent lag in the Host tracking algorithm.



**Figure 14. Flight #2 - Along Track Error**

## Summary

A sample of GPS data of 265 flights from January through February of 2005 was processed from the over 10,000 flights collected by the RVSM Certification Program. A total of 54,170 measurements were calculated comparing the GPS positions to time coincident Host radar track positions from all 20 Centers in the continental United States. This representative sample of operational data allowed the performance of the existing ATC tracking function to be estimated. Therefore, the results of this study provide a performance standard for the anticipated modernization of these ATC functions.

The comparison was made by calculating the distance in nautical miles between the XY location reported by the radar tracking data to the time coincident XY location reported by GPS. The later considered the true position of the aircraft. This distance, called the horizontal track error, is further divided into two orthogonal components- the along track error and the cross track error. The horizontal track error captures an error in the radar time stamp as well as a pure position measurement error. Large along track errors are generally time stamp errors rather than position errors, while cross track errors represent the side to side positional error.

The error rates were calculated for all of the measurements. The average horizontal error was 0.69 nautical miles or 4200 feet. The cross track error distribution is symmetrical about zero; however, the along track error distribution is strongly skewed in the negative direction. The radar position is therefore consistently lagging in

time. This bias in the data suggests that the Host radar data has an uncompensated delay.

For this study, the overall horizontal rms was reported at 0.78 nm. Previous studies used simulation methods to produce similar results. Trios Incorporated documented a steady state (no turns) rms values ranging from of 0.2 to 0.5 nm depending on the speed [1]. Trios also reported rms values of 0.7 to 1.7 nm for turns depending on speed and maneuver details. Since the study reported in this paper produced errors for all measurements, turns and steady state, and a mix of operational speeds (median about 350 knots), the results are fairly consistent.

Inferential statistics were also applied in this study to examine the relationship between the metrics (response variables) and other predictor variables including the Center, turn status (i.e. the track is within a turn or not), vertical transition status (i.e. track is climbing, descending or level), or altitude interval. Results evaluating the impact of operational Center were presented in this paper and confirmed that Center did not have a strong influence on tracking error.

To complement the statistical analyses on all the flights, a detailed overview of two individual flights within the study were presented as well. The average horizontal radar error in the first example was 0.80 nm with a maximum of 1.5 nm. For Flight Sample #1 in the plotted turn, the radar track swung wide of the GPS positions, being offset by 0.33 nm, and lagged the GPS positions by several seconds. On the straight part of the flight segment, the radar track wandered back and forth but the lag as shown by the time tags is still very small.

In the Sample Flight #2, the average horizontal radar error is 0.82 nm and the maximum 1.5 nm. The flight segment had relatively large cross track errors and along track errors on the straight part of the track and little error in the turn. In the first sample flight the errors in the turn are small; in the second sample the errors in the turn are large. The differences in the errors between the two examples illustrate that the errors can vary from flight to flight but are also consistent with the general observation discussed previously that the negative bias provides evidence of an uncompensated longitudinal error. For the cross track errors, the signed errors tend to cancel resulting in a sample

mean close to zero. Both sample flights produce this same result but the later exhibits larger cross track error compared to other flights, illustrating that the flight variability can be quite large when reviewing specific flights.

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*24<sup>th</sup> Digital Avionics Systems Conference  
October 30, 2005*